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3-D OPTICAL MEMORY DISK

Demetri Psaltis

Submitted to:

Dr. Alan E. Craig

Air Force Office of Scientific Research

Bolling Air Force Base, Washington, D. C.

Principal Investigator:

Dr. Demetri Psaltis

California Institute of Technology

Department of Electrical Engineering

Pasadena, California 91125

Abstract

Recently, a new method of multiplexing holograms by rotating the material, or equivalently, the recording beams was invented. This method is called Peristrophic (Greek for rotation) multiplexing and is briefly described. Peristrophic multiplexing can be combined with other multiplexing methods to increase the storage density of holographic storage systems such as the previously reported 3-D disk. Peristrophic multiplexing was experimentally demonstrated using DuPont's HRF-150 photopolymer film. A total of 295 holograms were multiplexed in a 38μm thick photopolymer disk by combining peristrophic multiplexing with angle multiplexing. In addition, it is shown that combining both angle and peristrophic multiplexing the storage density of 3-D disks is greatly enhanced.

1.0 Introduction

The number of holograms that can be multiplexed at a certain location on a holographic disk is primarily a function of two parameters – the system's bandwidth (either temporal or spatial frequency) and the material's dynamic range. Recently, thin film materials have been developed with relatively large dynamic range. An example of such a material is DuPont's HRF-150 photopolymer [1]. Previously we have reported 10 angle multiplexed holograms in a 38μm thick film [2] with diffraction efficiency of 10^{-3}. Since we can typically work with holographic diffraction efficiencies on the order of 10^{-6}, we have sufficient dynamic range to record significantly more than 10 holograms. The angular bandwidth limitation can be alleviated by making the film thicker [3] but scattering increases rapidly with thickness in these materials. Another method that has been previously used to increase the utilization of the available bandwidth of the system is fractal sampling grids [4,5].

In this report we describe the application of peristrophic (Greek for rotation) *multiplexing* to holographic 3-D disks. With this method the hologram is physically rotated with the axis of rotation being perpendicular to the film's surface every time a new hologram is stored. The rotation does two things. It shifts the reconstructed image away from the detector allowing a new hologram to be stored and viewed without interference. and it can also cause the stored hologram to become non-Bragg matched. This rotation is in addition to and separate from the conventional disk rotation. In addition, peristrophic multiplexing can be combined with other multiplexing techniques such as angle or wavelength multiplexing to increase the storage density and with spatial multiplexing to increase the storage capacity of the disk.

2.0 Theory for Peristrophic Multiplexing

The setup for peristrophic multiplexing Fourier plane holograms is shown in

Figure 1. The reference plane wave (R) is incident at an angle θ_r and the signal beam (S) is incident at an angle θ_s, both angles measured with respect to the film's normal. Taking the center pixel of the image as the signal and neglecting any effects due to hologram thickness, the hologram transmittance can be written as

$$R^* S = e^{-i2\pi\frac{\sin\theta_r}{\lambda}x} e^{-i2\pi\frac{\sin\theta_s}{\lambda}x} \tag{1}$$

The hologram is then rotated by $d\theta$ about the center of the x-y plane as shown in Figure 1. Assuming the rotation is small, this results in the coordinates being transformed according to: $x' \approx x - y d\theta$, and $y' \approx y + x d\theta$. Substituting these relations into Eq. 1, the hologram be expressed in terms of the unrotated coordinates (x, y)

$$R^* S = e^{-i\frac{2\pi\sin\theta_r x}{\lambda}} e^{-i\frac{2\pi\sin\theta_s x}{\lambda}} e^{-i\frac{2\pi(\sin\theta_s + \sin\theta_r)d\theta y}{\lambda}}. \tag{2}$$

After multiplying by R and Fourier transforming, the last term in Eq. 2 results a shift in the image. The rotation required to translate the image out of the detector aperture is approximately given by,

$$d\theta \geq \frac{\frac{d}{F}}{\sin\theta_s + \sin\theta_r}. \tag{3}$$

where d is the size of the image at the detector plane and F is the focal length of the lens used. For image plane holograms, the expression is [6]

$$d\theta \geq \frac{\frac{2\lambda}{\delta}}{\sin\theta_s + \sin\theta_r}, \tag{4}$$

where $1/\delta$ is the highest spatial frequency in the image. For image plane holograms, the undesired holograms are filtered out at the Fourier plane of the system. Notice that this method can be combined with other volumetric multiplexing methods to further increase the storage density.

The Bragg selectivity, assuming the reference is given by $R = e^{-i(\frac{2\pi\sin\theta_r}{\lambda}x + \frac{2\pi\cos\theta_r}{\lambda}z)}$ and the signal given by $S = e^{i(\frac{2\pi\sin\theta_s}{\lambda}x + \frac{2\pi\cos\theta_s}{\lambda}z)}$, can be calculated using the Born and

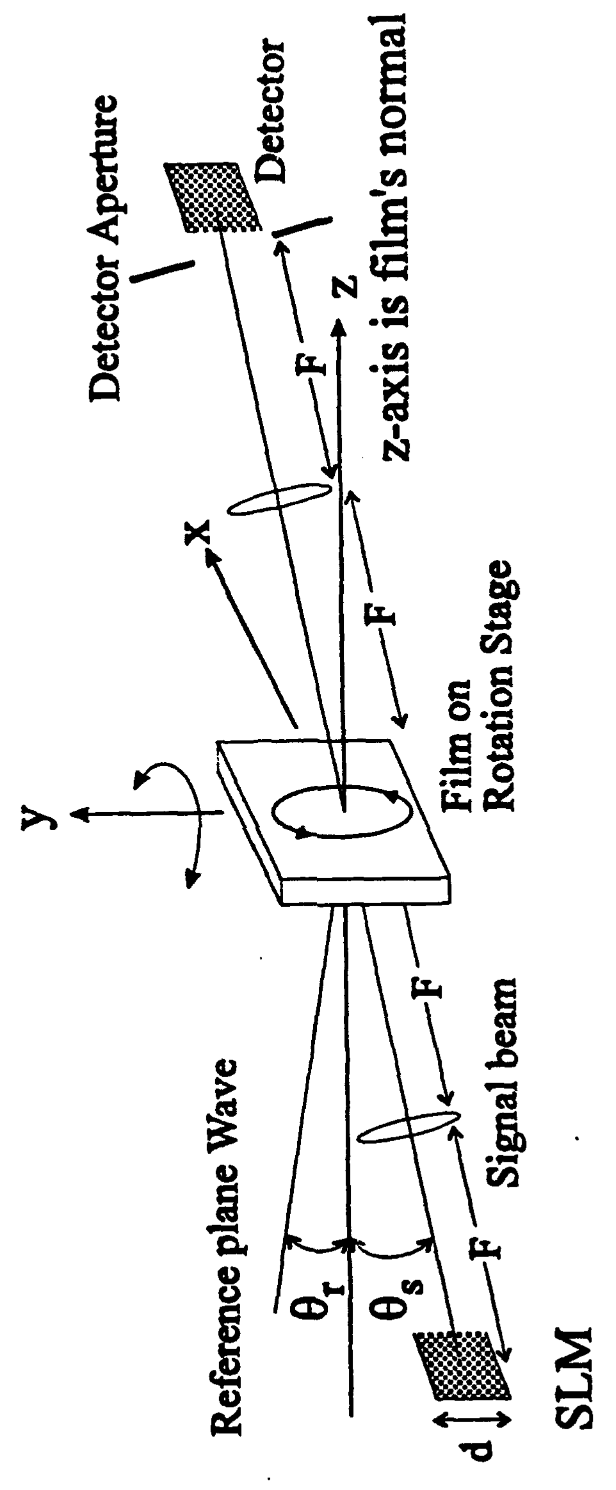

Figure 1: Setup for peristrophic multiplexing.

paraxial approximations and integrating over the volume of the hologram. Assuming that the tranverse (x, y) dimensions of the film are much larger than the bandwidth of the images, the Bragg selectivity can be shown to be

$$d\theta = \sqrt{\frac{2\lambda}{t}\left(\frac{\cos\theta_s}{\sin\theta_r(\sin\theta_s + \sin\theta_r)}\right)}\,, \tag{5}$$

where t is the thickness of the material. Using $\lambda = 488\text{nm}$, $t = 38\mu\text{m}$, and $\theta_s = \theta_r = 30°$ results in a selectivity of about 12°. The Bragg matching requirement is the dominant effect if $\frac{d}{F} > \sqrt{2\lambda\cos\theta_s(\sin\theta_s + \sin\theta_r)/t\sin\theta_r}$. For most material thicknesses, the Bragg matching criterion determines the required rotation for peristrophic multiplexing. In our experiments, because the thickness of the film is only 38μm, the image could be filtered out before the gratings become non-Bragg matched.

3.0 Experimental Results

The experimental setup is the same as in Fig. 1 except a rotation stage was added to rotate the film around a vertical axis as well as around the film's normal. This makes it possible to combine peristrophic and angle multiplexing. The film was located a significant distance from the Fourier plane so that the siganl beam was approximately uniform. For each peristrophic position, multiple holograms are stored using standard angle multiplexing by rotating the medium. A spatial light modulator (SLM) was used to present images (cartoons) to the system. Each frame is numbered according to the sequence in which they were stored. The reference and signal beams were initially incident at ±30° from the film's normal. The reference beam intensity was 1.1 mW/cm^2 and the signal beam had 300 μW in about a 1 cm by 0.5 cm area. The film was rotated in-plane by 3° between each set of angle multiplexed holograms to enable the other holograms to be filtered out. Eq. 3 predicts a required rotation of about 9° for Fourier plane hologram while Eq. 4 predicts about 1.7° rotation for image plane. The 3° was experimentally obseved

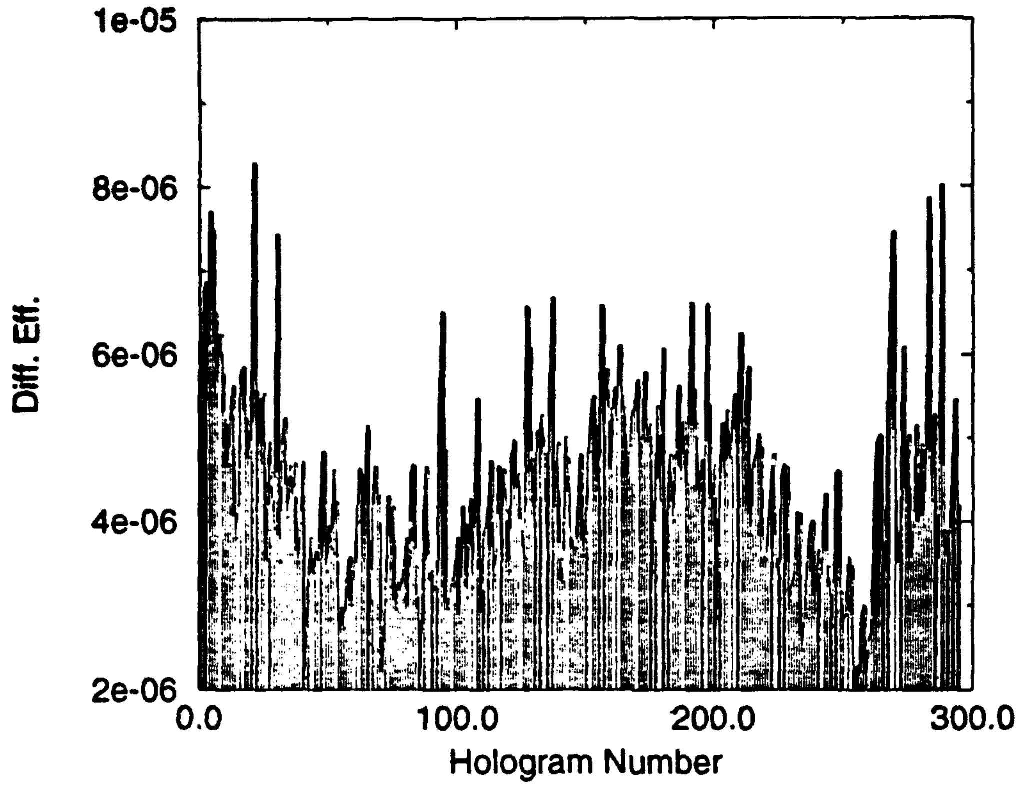

Figure 2: Diffraction efficiency vs hologram number for 295 holograms stored in 38 μm thick film.

for the in-between (Fresnel) case we used. Each angle multiplexed hologram was also separated by 3°. The initial exposure time was 0.11 seconds, but starting at hologram number 26, each hologram was exposed for 0.005 seconds longer than the previous hologram to correct for the lost sensitivity due to run time [2]. There was a 1.5 second delay between holograms to allow the rotation stages to completely stop. 295 holograms were stored in the polymer by peristrophic multiplexing 59 times and storing 5 angle multiplexed holograms with each peristrophic position. The diffraction efficiency of the 295 holograms is plotted in Fig. 2. The average efficiency was $\sim 4 \times 10^{-6}$ and the variations are primarily due to variation in the average intensity of the frames. In separate experiment, we stored equal amplitude plane wave holograms and observed a decrease in diffraction efficiency proportional to $1/M^2$ [7].

Previously we stored $M = 10$ holograms with roughly 10^{-3} diffraction efficiency [2] limited by the angular bandwidth of the optical system. Peristrophic multiplexing made it possible to store $M = 295$ holograms at the same location with a diffraction efficiency of $\sim 4 \times 10^{-6}$. Thus, peristrophic multiplexing allowed for almost two orders of magnitude increase in the storage capacity of the DuPont photopolymer and changed the limiting factor from the angular bandwidth of the optical system to the dynamic range of the material.

4.0 Architecture

Figure 3 shows the implementation of a 3-D holographic disk that uses spatial, angle and peristrophic multiplexing. The information to be recorded is presented by a spatial light modulator (SLM) which modulates the signal beam. The reference beam then interferes with the signal beam and the information is recorded throughout the volume of storage medium where the two beams overlap. The surface density can be increased by using angle multiplexing (changing the angle between the reference beam and the signal beam) to record more holograms in the same volume. To further increase the storage density, the reference beam is also rotated about the signal beam to implement peristrophic multiplexing. This rotation of the reference beam either shifts the reconstructed images from the previously recorded holograms off the detector or the stored holograms becomes Bragg mis-matched, allowing for more holograms to be recorded. The storage capacity of the system is increased by rotating the storage medium to record at non-overlapping regions on the disk (spatial multiplexing). Figure 4 shows the theoretical surface density and the number of holograms that can be multiplexed at a given location on the disk as a function of the storage medium's thickness using the implementation shown in Figure 3. The geometry limited density was calculated using the parameters shown in Figure 4. The density is approximately 10 bits per micron squared for a medium

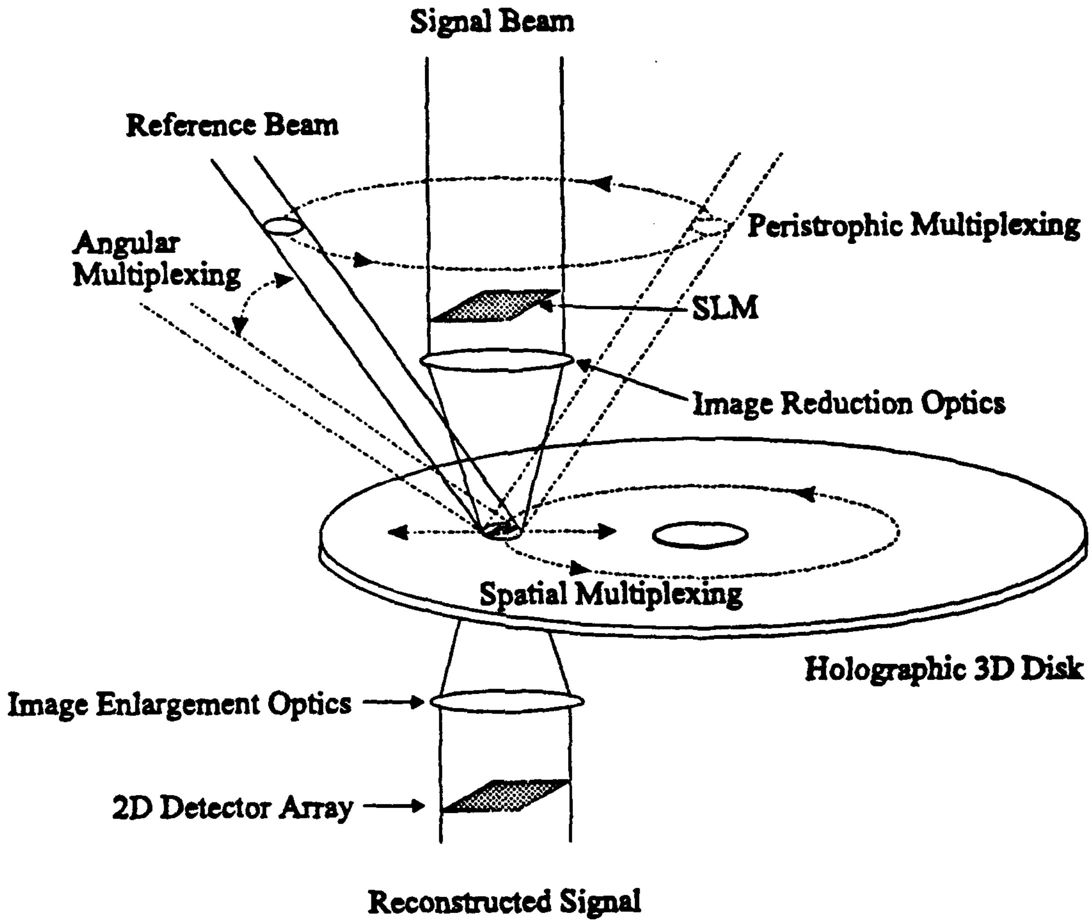

Figure 3: 3-D holographic disk system using both angle and peristrophic multiplexing.

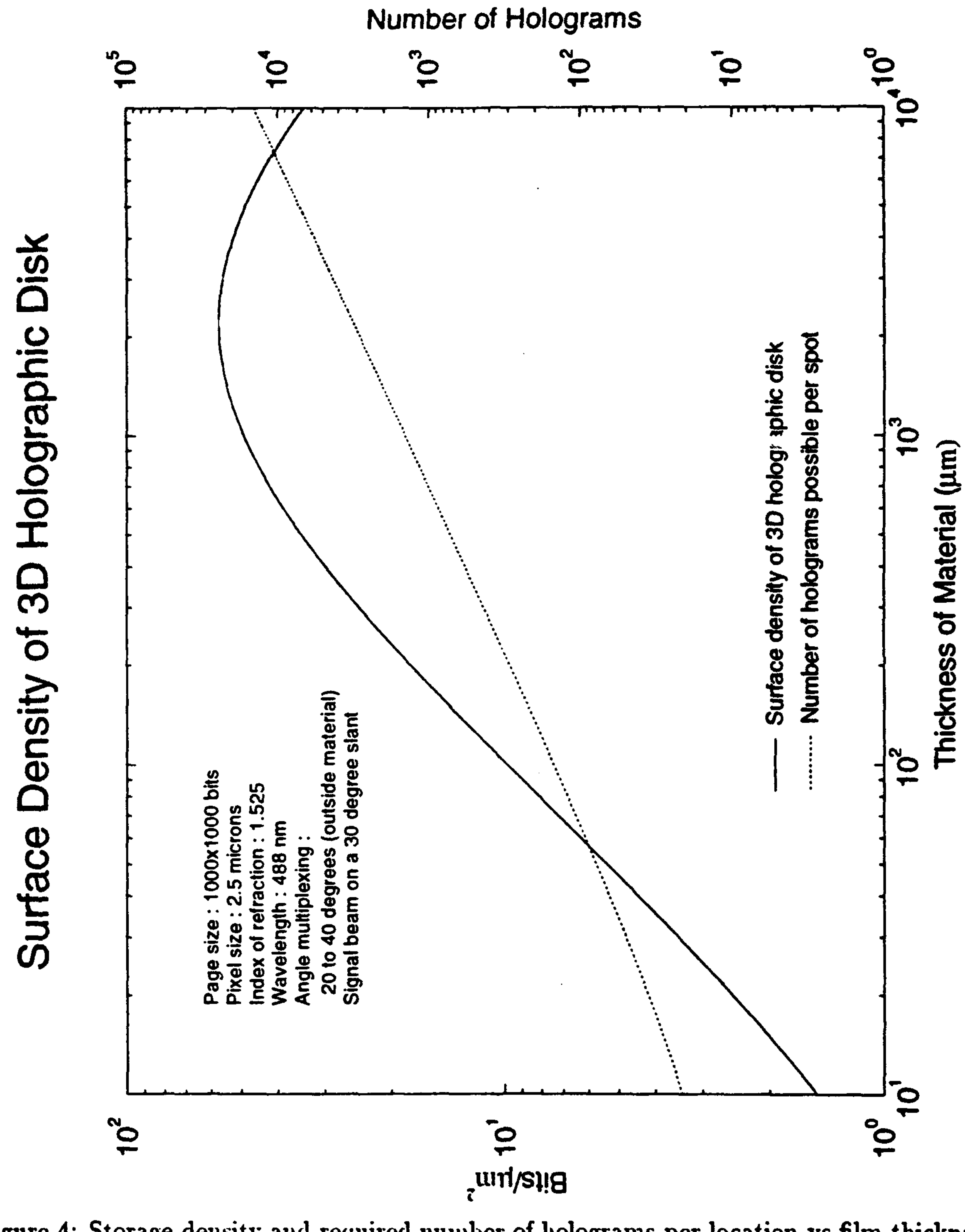

Figure 4: Storage density and required number of holograms per location vs film thickness for a 3-D disk that utilizes both peristrophic and angle multiplexing.

thickness of only 0.1mm. This density is achieved by storing roughly 150 holograms with a page size of 10^3x10^3 bits. The density does not grow continuously as a function of increasing thickness even though the number of multiplexed hologram increases. This is due to the fact that light defocuses and requires more area as the material gets thicker. The storage medium for the 3-D holographic disk can be any holographic material such as photorefractives and photopolymers. Photorefractives are re-programmable, optically erasable and can be made to large thickness with good optical quality. Recently, 10,000 holograms were recorded at one location in LiNbO3 [8] and could be reconstructed with high fidelity. Photopolymers on the other hand are inexpensive, easy to use and offer non-volatile storage. We have previously recorded 300 holograms - 3 at each location, 100 spatial locations on a ring around a photopolymer disk. Thus we have demonstrated all the aspects of the 3-D holographic disk system. Currently we are working on demonstrating storage densities close to the theoretically predicted limits.

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